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Int. CL:—H 03 k 19/14.

COMPLETE SPECIFICATION

Electro-Optical Digital System

We, RADIO CORPORATION OF AMERICA, a Corporation organized under the laws of the State of Delaware, United States of America, of 30, Rockefeller Plaza, City and State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly 10 described in and by the following statement:—

This invention relates to electro-optical digital systems for performing logic functions in electronic data processing apparatus, 15 and particularly to systems employing one or more of the following types of solid-state devices: p-n junction photodiodes, negative-resistance or tunnel diodes and laser diodes.

20 The speed of operation of a digital binary information-handling system depends on: the speed with which the devices used therein can switch between two distinct "0" and "1" information states; the speed with 25 which "0" and "1" information signals can be transmitted from one device to a logically following device or devices, and the signal gain or "fan-out" characteristic of the devices used. Previously known systems 30 have been limited in speed of operation by one or another of these factors. For example, systems utilizing the very fast switching characteristics of tunnel diode devices have been limited by strict tolerance requirements and limited signal fan-out abilities.

35 It is therefore a general object of this invention to provide an improved electro-optical digital system.

With respect to a preferred form of the [Price]

invention, it is an object thereof to provide 40 an improved digital system wherein logic circuit units are very fast in switching between "0" and "1" states, and are capable of propagating standard-level signals at the speed of light in a transmission medium to 45 a large number of other logic units.

It is another object of a preferred form of the invention to provide an improved digital system wherein "0" and "1" information signals are represented by the 50 absence or presence of coherent light, and wherein a p-n junction photodiode and a negative resistance diode (tunnel diode) are used to establish a switching threshold for distinguishing between "0" and "1" input 55 light signals.

According to the present invention we provide an electro-optical digital logic system comprising at least one input signal source, a two-state circuit having an output 60 current path, said signal source and two-state circuit being coupled and arranged whereby said output path carries currents of either a lesser or a greater magnitude in response to the one or more signals appearing in said signal source, and a laser diode 65 coupled with said output path from said two-state circuit in a manner whereby the said laser diode is caused to emit coherent light either only in response to the presence 70 of said lesser currents in said output path or only in response to the presence of said greater currents in said output path.

In one example there is provided a tunnel diode circuit having a low voltage state and 75 a high voltage state. The state of the tunnel diode is controlled by an input-light-signal-responsive back-biased p-n junction photo-

diode electrically connected to the tunnel diode. A coherent-light-emitting laser diode is electrically connected to the tunnel diode circuit so that the laser diode receives an 5 amount of current determined by the state of the tunnel diode.

In addition, if desired, a p-n junction diode light amplifier may be positioned to receive and amplify a coherent light output 10 signal generated by the laser diode. The light output signal from the light amplifier may be directed by means of an optical light splitter to the light inputs of many other similar systems in a logic-performing 15 apparatus.

Referring to the accompanying drawings:

Figure 1 illustrates one example of an electro-optical system according to the invention;

20 Figures 2 and 3 are characteristic charts referred to below;

Figure 4 is an inverter circuit which may be substituted for part of the system of Figure 1;

25 Figure 5 is a further characteristic chart;

Figure 6 illustrates another example of a system according to the invention.

Referring to Figure 1, there is shown a tunnel diode circuit including, in series, a 30 negative resistance or tunnel diode 10, a junction point 11, an inductor 12 and a positive terminal V_2 of a direct current bias source providing a positive voltage in relation to a ground or reference value. The 35 tunnel diode 10 is preferably a gallium arsenide diode having the usual current-voltage character 10' as shown in Figure 3, and having a peak current sufficiently higher than its valley current so that its 40 output current exceeds the lasing threshold of a laser diode to be described.

A laser diode 14 is connected as a load across the tunnel diode 10. The laser diode 14, when viewed as a load on the tunnel 45 diode 10, may have a current-voltage characteristic 14' as shown in Figure 3. A laser diode may consist of a gallium arsenide wafer having a planar p-n junction extending to edges of the wafer. Two 50 opposite edges of the wafer are spaced an appropriate distance apart and are partially reflecting so that when a sufficient electrical current is supplied to the terminals of the diode, coherent light oscillations build up 55 in the planar junction and are radiated from an edge of the wafer.

A light-signal responsive input circuit for the tunnel diode 10 includes a plurality of photodiodes 18 connected in parallel 60 between the positive terminals V_1 of a bias source and the anode terminal 11 of the tunnel diode 10. The p-n junction photodiodes 18 are preferably silicon diodes.

The p-n junction photodiodes 18 in 65 Figure 1 are back-biased by having their

cathodes connected to positive voltage sources V_1 . When a photodiode is thus back-biased, and when no input light signal is applied to the diode, the diode presents a high impedance to the flow of current in 70 the reverse direction through the diode as represented by the current-voltage characteristic 18' in the chart of Figure 2. On the other hand, when an input light signal is supplied to the junction region of the back-biased photodiode, a large reverse current flows through the diode as represented by the characteristic 18" in Figure 2. The substantially horizontal disposition of the left-biased portion of the characteristic 18" 80 indicates that the reverse current flowing through the photodiode is substantially constant over a considerable range of values of reverse voltage across the photodiode. A reverse current through a photodiode 18 passes in the forward direction through the 85 tunnel diode 10.

A p-n junction diode light amplifier 20 in Figure 1 is positioned to receive coherent light radiated from the laser diode 14 over the path 21. The amplifier diode 20, in turn, radiates an amplified, directional, coherent light signal over the path 22. In the absence of a coherent light input to the amplifier diode 20, its light output is 90 non-directional and non-coherent. The light amplifier diode 20 is part of a light amplifier circuit which also includes a resistor 24 and the positive terminal V_3 of a voltage source. The resistor 24 and the voltage at 95 terminal V_3 constitute a substantially constant current bias source for the light amplifier diode 20. The light amplifier diode 20 is preferably a gallium arsenide diode similar to the laser diode 14 but differing 100 from the laser diode 14 in some of its physical dimensions. The amplifier diode 20 is also different in having light-transmitting coatings on the edge of the wafer to which light is supplied over the path 21, and on 105 the edge from which amplified light is transmitted over path 22.

The amplified light output from the light amplifier diode 20 is applied over path 22 to the input of an optical light splitter 25. 115 The light splitter 25 may consist of optical fibers for splitting and directing light over paths 26 to individual photodiodes, corresponding with the photodiodes 18, of other following units in a logic system. The light splitter 25 may, alternatively, consist of a system of partially and totally reflective surfaces providing separated and substantially equal-intensity light signals along 120 separated paths 26.

The number of signal inputs 19 (fan-in) and the number of signal outputs 26 (fan-out) may be fewer or considerably greater 125 in number than the illustrative number shown in Figure 1. The values shown for 130

bias sources and circuit elements are suggested illustrative values, subject to engineering modification.

All of the presently-known photodiodes, 5 laser diodes and light amplifying diodes suitable for use in the arrangement of Figure 1 are operable at very high speeds and have the desired characteristics when they are maintained at temperatures considerably 10 lower than room temperatures. It is therefore desirable, at the present time, to operate the arrangement of Figure 1 at a reduced temperature such as the temperature of liquid nitrogen (-178°C.) or liquid air. It 15 is contemplated that semiconductor laser devices available in the future may be capable of operation with the desired characteristics at room temperatures. Available photodiodes and tunnel diodes operate 20 satisfactorily at room temperatures and they operate as well or even better at greatly reduced temperatures. The photodiodes, laser diodes, light amplifying diodes and tunnel diodes are all switchable from one 25 condition to another in a fraction of a nanosecond (in a fraction of a thousandth of a microsecond).

In operation, the arrangement of Figure 1 may be employed as an "or" gate, or as 30 an "and" gate, for light signals, by appropriately adjusting the electric bias sources. If operation as an "or" gate is desired, the tunnel diode 10 and the laser diode 14 are biased to provide the characteristics 35 relationship of curves 10' and 14' in Figure 3. The tunnel diode 10 is normally in its low-voltage, high-current state represented by the point A. In this normal condition, with the voltage V_1 across the laser diode 40 14, the laser diode 14 presents a high impedance and very little current flows through it. Substantially all of the current from the source V_2 flows through the tunnel diode 10.

45 In the absence of an input light signal directed over paths 19 to any one of the photodiodes 18, the back-biased photodiodes 18 present a high impedance to a reverse flow of current as represented by 50 the characteristic 18' in Figure 2. When a light signal is directed over a path 19 to one of the photodiodes 18, the current-voltage characteristic of the photodiode changes and becomes the characteristic 18". 55 Under this condition, a large reverse current is permitted to flow through the photodiode 18 from the bias terminal V_1 to the anode terminal 11 of the tunnel diode 10. This additional current supplied in the forward direction through the tunnel diode 10 causes its operating point to rise from the point A over the current peak of the characteristic shown in Figure 3, and to switch rapidly to the right to its high voltage 60 state with an operating point at B.

When the tunnel diode is in its high voltage state as represented by the point B, most of the current which was previously flowing from the V_2 terminal through the tunnel diode 10 is diverted to the parallel 70 path including the laser diode 14. The current now flowing through the laser diode 14 is of sufficient magnitude to cause lasing in the diode 14 and the emission of high-intensity coherent light over the path 21. 75 The coherent light output of laser diode 14 is amplified in the light amplifier diode 20 and is directed through the light splitter to inputs of other logic units.

The tunnel diode circuit shown is a monostable circuit in which the operating point of the tunnel diode 10 automatically returns from the operating point B to the normal operating point A after a period of time determined primarily by the value 80 of the inductor 12. When the tunnel diode 10 returns to the operating point A, the current previously supplied to the laser diode 14 is diverted back to the tunnel diode 10 and the laser diode 14 ceases to generate 85 a coherent light output.

In summary, an input light signal pulse applied to a photodiode 18 results in a plurality of output light pulses of standard 90 duration from the light splitter 25.

If the arrangement of Figure 1 is desired to operate as an "and" gate, the biasing of the tunnel diode 10 is arranged so that all of the input photodiodes 18 must be receiving input light signals at the same time in 95 order that they can supply enough current to the tunnel diode 10 to switch its operating point from point A, over the current peak, to point B. In other respects, the operation will be understood from what is 100 described above.

Figure 4 shows an inverter circuit wherein the presence of an input light signal 105 results in the absence of an output light signal 32, and vice versa. The inverter 110 circuit includes the positive terminal V_1 of a bias source connected in series in the order named through an inductor 34, a junction point 35, a tunnel diode 36 (anode to cathode) and a laser diode 38 (anode 115 to cathode). A p-n junction diode 40 is connected between the junction point 35 and a positive terminal V_2 of a bias source. The diode 40 is preferably a p-n junction diode which has electrical characteristics 120 similar to the electrical characteristics of the laser diode 38, but which need not have any optical characteristics. A photodiode 42 is connected in back-biased relation between the positive terminal V_1 of a bias source 125 and the anode terminal 35 of the tunnel diode 36.

The current-voltage characteristic of the series combination of the tunnel diode 36 and the laser diode 38 is a characteristic 130

37 as represented in Figure 5. The characteristic 37 is derived graphically by adding the separate characteristics of the tunnel diode and the laser diode, in the voltage direction E. The p-n junction diode 40 is biased by the positive voltage source V_1 to provide the load characteristic 40' in the desired relationship with the characteristic 37, i.e. to provide one stable intersection 10 at a low voltage, high current point A and another stable intersection at a high voltage, low current point B. The voltage source V_1 may, if desired, be replaced by another p-n junction diode in series with 15 the p-n junction diode 40 to provide the load characteristic 40'.

In the operation of the light signal inverter circuit of Figure 4, current normally flows from the bias terminal V_1 through 20 the inductor 34, the tunnel diode 36 and the laser diode 38. The operating point of the tunnel diode and laser diode characteristic 37 is normally at the point A. Substantially no current normally flows through 25 the diode 40. The large current flowing through the tunnel diode 36 and the laser diode 38 causes coherent light to be normally emitted over the path 32 from the laser diode 38.

30 The normal condition of the circuit of Figure 4, which has been described, is the condition existing when there is no input light signal applied over path 30 to the photodiode 42. When an input light signal 35 is applied to the photodiode 42, current flows from the bias terminal V_1 and through the photodiode 42 to the tunnel diode 36, causing the operating point of the tunnel diode to switch from point A to point B. 40 When this happens, the majority of the current which was previously flowing through the tunnel diode 36 and the laser diode 38 is diverted to the parallel path including the diode 40. The reduction in 45 current through the laser diode 38 causes it to cease emitting coherent light. The laser diode 38 does not resume the emission of coherent light until after the operating point of the tunnel diode switches back to the 50 low voltage, high current state operating point A at a time determined primarily by the reactive effect of the inductor 34.

The inverted light output supplied at 32 by the circuit of Figure 4 results from the 55 fact that the laser diode 38 is in series with the tunnel diode 36, rather than being in parallel with the tunnel diode as is the case in the arrangement of Figure 1. The light signal output 32 from the laser diode 38 in Figure 4 may be supplied to a light amplifying diode 20 and a light splitter 24 as shown in Figure 1 before being directed to the input of another following logic unit.

60 Figure 6 shows a bistable circuit which 65 supplies an output light signal from a set

output 50 after having received an input light signal at a set input 52, and which supplies an output light signal from a reset output 54 after having received an input light signal at a reset input 56. The circuit 70 of Figure 6 includes, in series, a positive terminal V_1 of a bias source, a resistive impedance 58, a junction point 59, a tunnel diode 60 and a laser diode 62. The bias voltage at terminal V_1 and the resistor 58 75 are selected to constitute a substantially constant-current source connected to the junction point 59.

The laser diode 64 and a dummy diode 66 are connected in series from the junction point 59 to the circuit return path represented by ground. A first photodiode 68 is connected in back-biased relation between the positive bias source V_1 and the junction point 59. A second photodiode 70, for reset 85 purposes, is connected in back biased relationship between a negative bias source terminal V_2 and the junction point 59.

The combined characteristic of the tunnel diode 60 and the laser diode 62 may be as 90 represented by the characteristic 37 in Figure 5; and the load characteristic of the laser diode 64 and the dummy diode 66 may be a characteristic such as characteristic 40' in Figure 5. The use of a resistor 58 in 95 Figure 5, instead of the inductor 34 in Figure 4, makes the circuit of Figure 6 a bistable circuit having stable operating points at A and B.

In the operation of the circuit of Figure 100 6, it is initially assumed that the circuit is in its reset condition with the tunnel diode 60 in its low voltage state and with its operating point at the point A in Figure 5. Under this condition, a large current flows 105 through the tunnel diode 60 and the laser diode 62 causing the laser diode 62 to emit coherent light as a reset output signal at 54.

If an input light signal is now applied 110 at the set input 52 to the photodiode 68, the photodiode 68 becomes conductive and the current flowing to the anode terminal 59 of the tunnel diode 60 causes the tunnel diode to switch to its high voltage state 115 with an operating point at B. When this happens, the current previously flowing through tunnel diode 60 and laser diode 62 is diverted to the laser diode 64. This causes laser diode 62 to cease emitting light, 120 and causes laser diode 64 to emit set output coherent light at 50. The circuit will remain indefinitely in this condition, providing a coherent output light signal 50 from the set output of the circuit. 125

To reset the circuit of Figure 6, a light signal is applied at 56 to the reset input photodiode 70. The light impinging on photodiode 70 changes its electrical characteristic so that it passes current from the 130

- junction point 59 in the reverse direction through the photodiode 70 to the bias terminal V_7 . This current flow reduces the current supplied previously from the terminal V_6 to the tunnel diode 60. The reduction in current available to the tunnel diode 60 causes its operating point to switch from the point B back to the low voltage state operating point A. When in the low voltage operating state, the increased current through the tunnel diode and the laser diode 62 causes a reset light signal output at 54. At the same time, the current through laser diode 64 is reduced so that the set output light at 50 ceases. The circuit of Figure 6 always provides one or the other of its two coherent light signal outputs depending on which of its inputs most recently received an input light signal.
- 20 The outputs from the bistable circuit of Figure 6 may each be amplified and split by a light amplifier and light splitter as shown in Figure 1. It will be understood that the inverter circuit of Figure 4 and the bistable circuit of Figure 6 may be provided with multiple photodiode input circuits after the manner illustrated in Figure 1.
- 25 The logic units shown and described employ various semi-conductor devices all of which have high inherent operating speeds. The semi-conductor devices are used in a way providing a clear threshold distinguishing "0" and "1" information conditions. The logic units have a high fan-out capability. That is, a logic unit is capable, in the performance of logic functions, of providing many standard-level light output signals for application to inputs of many following logic units. Also, output signals in the form of coherent light can be transmitted from the output of one logic unit to the input of another logic unit at the speed of light in a transmission medium.
- 30 **WHAT WE CLAIM IS:—**
- 45 1. An electro-optical digital logic system comprising at least one input signal source, a two-state circuit having an output current path, said signal source and two-state circuit being coupled and arranged whereby said output path carries currents of either a lesser or a greater magnitude in response to the one or more signals appearing in said signal source, and a laser diode coupled with said output path from said two-state circuit in a manner whereby the said laser diode is caused to emit coherent light only in response to the presence of said lesser currents in said output path.
- 50 2. An electro-optical digital logic system comprising at least one input signal source, a two-state circuit having an output current path, said signal source and two-state circuit being coupled and arranged whereby said output path carries currents of either a lesser or a greater magnitude in response to the presence of said lesser currents in said output path.
- 55 3. An electro-optical system according to claim 1 or 2, wherein said two-state circuit includes a tunnel diode biased for monostable operation.
- 60 4. An electro-optical system according to claim 1 or 2, wherein said two-state circuit includes a tunnel diode biased for bistable operation.
- 65 5. An electro-optical system according to claim 1 or 2, or 3, wherein each of said one or more input signal sources includes a light responsive device.
- 70 6. An electro-optical system according to claim 3 or 4 and 5, wherein the circuit parameters are selected so that said tunnel diode switches from one current state to the other current state in response to one or more light signals impinging on the said light responsive device or devices.
- 75 7. An electro-optical system according to any of the preceding claims, wherein a light amplifier is positioned to receive and amplify coherent light from said laser diode.
- 80 8. An electro-optical system according to claim 7, wherein a light splitter is positioned to direct light from said light amplifier to inputs of a plurality of other light signal systems.
- 85 9. An electro-optical system according to claim 3 or 4, wherein said tunnel diodes and laser diode are connected in a parallel circuit, said tunnel diode being in one current path of said parallel circuit and said laser diode being in another current path of said parallel circuit, and wherein a bias current source is connected to supply a current to said parallel circuit.
- 90 10. An electro-optical system according to claim 9, wherein the arrangement is such that the current to said parallel circuit flows preponderently through said tunnel diode when the said tunnel diode is in a low-voltage state and which flows preponderently through said laser diode when the tunnel diode is in a high voltage state.
- 95 11. An electro-optical system according to claim 10, wherein said input signal source comprises a back-biased p-n junction photodiode coupled to said tunnel diode in a manner such that the voltage state of said tunnel diode is changed in response to the presence or absence of a light signal.
- 100 12. An electro-optical system according to claim 11, wherein a laser diode is connected in series with said tunnel diode.
- 105 13. An electro-optical system according to claim 1 or 2, comprising a parallel circuit having one parallel current path which

- includes the series combination of said two-state circuit and said laser diode, said two-state circuit comprising a first tunnel diode, and the system having another parallel 5 current path which includes a second laser diode, a bias current source connected to supply a current to said parallel circuit which flows preponderently through said tunnel diode and first-mentioned laser 10 diode when the tunnel diode is in its low-voltage state and which flows preponderently through said second laser diode when the tunnel diode is in its high-voltage state.
- 15 14. An electro-optical system according to claim 13, wherein said input signal source includes two oppositely-poled back-biased p-n junction photodiode detectors coupled to said tunnel diode, whereby a light signal 20 impinging on one of said photodiode detectors causes said tunnel diode to switch from its low voltage state to its high-voltage state, and whereby a light signal impinging on the other one of said photodiode 25 detectors causes said tunnel diode to switch from its high-voltage state to its low-voltage state.
15. A system according to claim 14, including in addition, first and second p-n junction light amplifiers positioned to 30 receive and amplify coherent light from said first and second laser diodes, respectively.
16. An electro-optical digital system substantially as herein described and illustrated with reference to Figure 1 of the 35 accompanying drawings.
17. An electro-optical digital system substantially as herein described and illustrated with reference to Figure 4 of the accompanying drawings. 40
18. An electro-optical digital system substantially as herein described and illustrated with reference to Figure 6 of the accompanying drawings.

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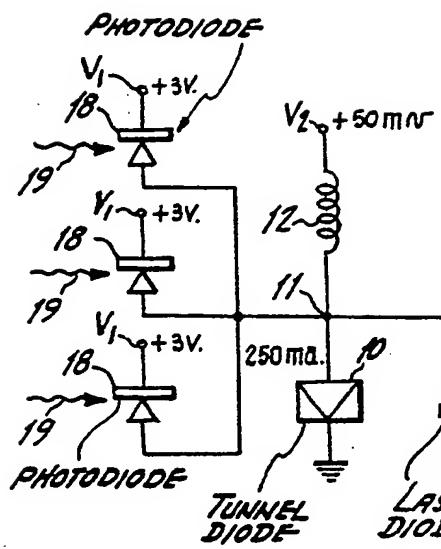


Fig. 1.

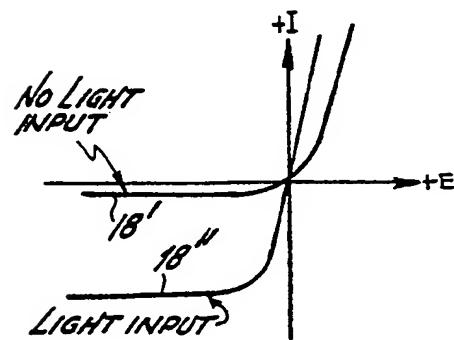
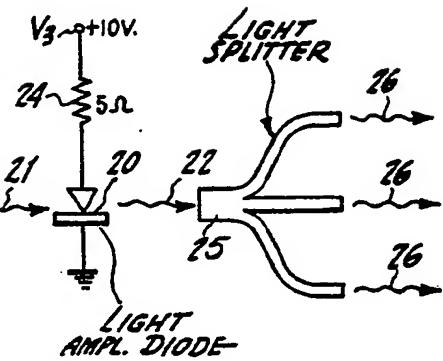


Fig. 2.

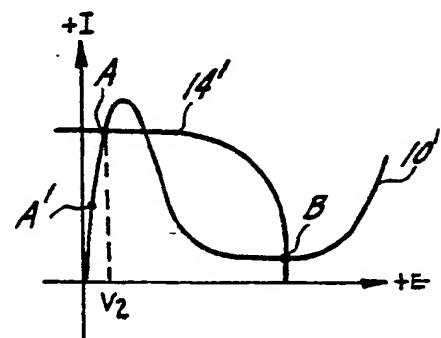


Fig. 3.

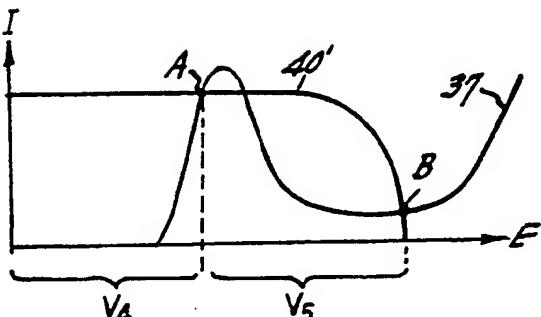
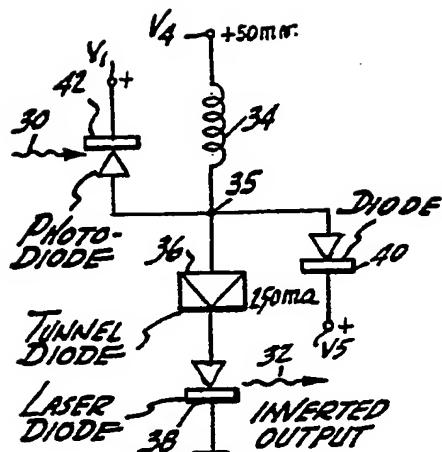


Fig. 5.

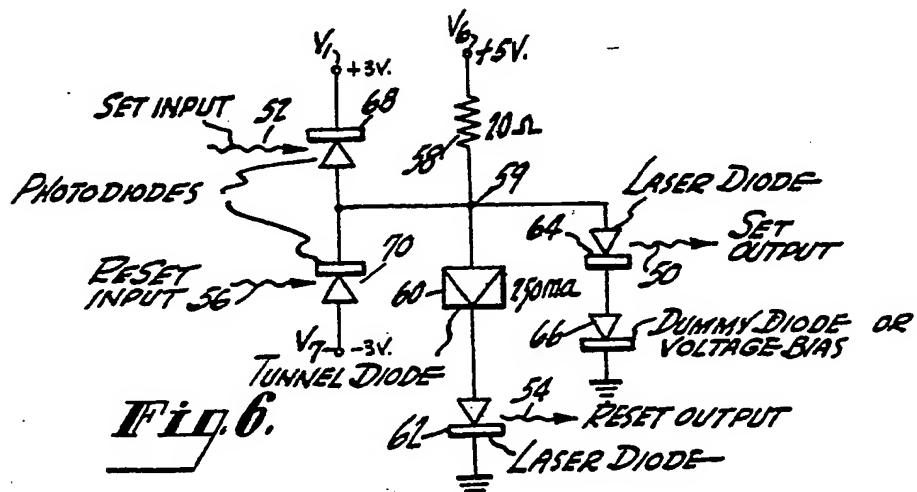


Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

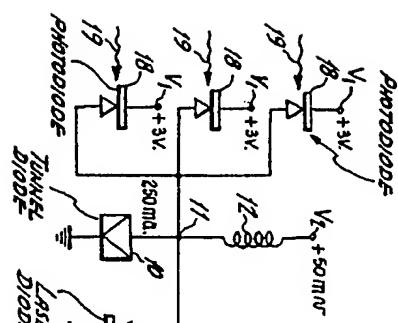


Fig. 1.

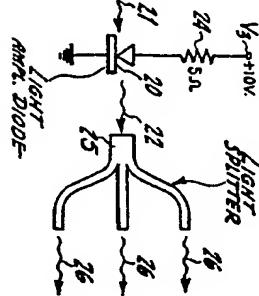


Fig. 2.

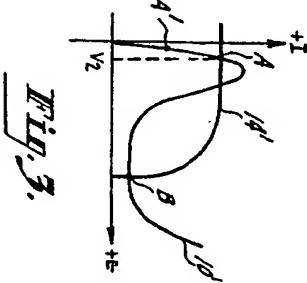
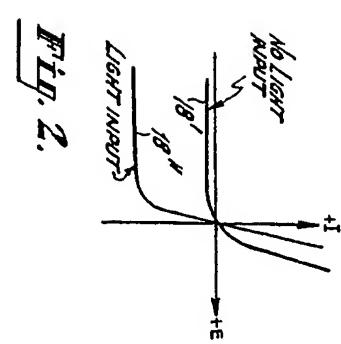


Fig. 3.

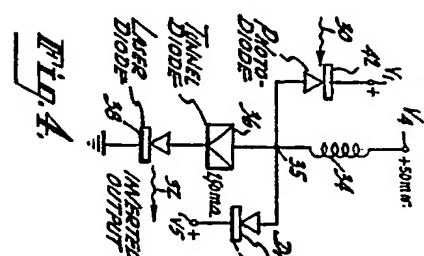


Fig. 4.

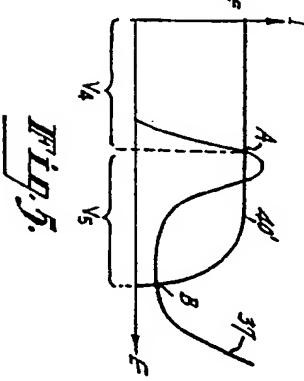


Fig. 5.

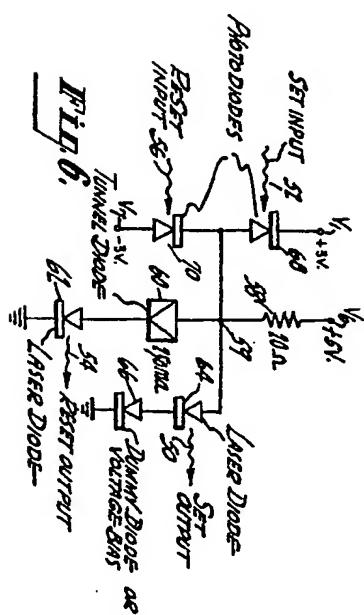


Fig. 6.